STRENGTH AND WEAR OF PLASTIC SHREDDER BLADES BASED ON DIFFERENT ORIENTATIONS AND GEOMETRIES

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ABSTRACT

Plastic pollution has become a worldwide issue and requires adequate awareness to solve the plastic waste management and disposal processes. Alternatively, recycling initiatives are important. The plastic shredder machine is a preliminary machine for shredding plastic waste before converting it into a functional commodity. Shredder machine designs for industrial, small to medium businesses, or individuals are readily available. However, the shredding output is constrained by the configuration of the blades, where inconsistent plastic distribution was observed. Therefore, certain sections of the blades experience more load compared to others. Shredder blade is the main components of a shredder machine used in plastic recycling. The validation of the shredder blades' design is essential to justify the suitability and safety of the design for the blade's installation in the shredder machine. Various edge angle (20°, 35° and 50°) of the shredder blade was analysed. The shredder blade with edge angle of 35° was chosen as it might provide a better shredding performance with larger grabbing curve. The maximum von Mises stress, displacement, and shear stress along with the minimum safety factor of the double and triple edges shredder blade towards the shredding of the Polyethylene Terephthalate (PET) sheet was analysed using Finite Element Analysis by Fusion 360 software. The result based on 1000N reaction force showed the maximum von Mises stress between 159.70 MPa to 184.80 MPa, maximum total displacement deformation of 0.03752 mm – 0.04611 mm, maximum shear stress of 50.85 MPa – 71.86 MPa, and safety factor of 1.95 – 2.25 for both double and triple edges shredder blade. The design of both blades is acceptable and safe since the safety factor is higher than the lowest safety factor standard of 1.5 based on the allowable stress code standard. A performance study was conducted on shredder blade using double and triple edges geometries with three different orientations which are spiral, V-orientation and series to understand its wear and shredding mechanism. Series orientated shredder blades were excluded due to high torsion were created caused the permanent deformation on the shredder machine's part. Identification of the loading distribution along the shredder blades was observed in different orientations. The microstructure and hardness of the worn cutting edge and as-received shredder blade were characterised by optical microscopy, scanning electron microscopy along with energy dispersive X-ray (EDX), X-ray diffraction analysis (XRD) and hardness testing. Wear mechanism in the shredder blades were categorised as progressive wear. The progressive wear was due to the abrasive, adhesive, and oxidation wear. Abrasive wear as the major progressive wear mechanism has been confirmed based on the shredding mechanism and microstructure analysis on the blades. An increase in oxygen element in EDX and the presence of magnetite and hematite in XRD analysis proven the oxidation wear occurred at the crack and dents on the blades' surface. Recycling efficiency, shredding efficiency, and percentage retention are the parameters used to evaluate the performance of the shredder blades. The shredding efficiency in all geometries and orientation ranged between 64.83 ± 0.69% to 69.53 ± 1.32% and is highly efficient in recycling of PET plastic with recycling efficiency above 95%. The best combination of the geometry and orientation is the double edges shredder blade with spiral orientation, which exhibited recycling efficiency at 97.39 ± 0.04%, shredding efficiency at 69.53 ± 1.32%, and retention at 2.61 ± 0.04%, along with a fewer number of blades recorded severe wear.

ABSTRAK

KEKUATAN DAN KEHAUSAN BILAH PLASTIK BERDASARKAN VARIASI ORIENTASI DAN GEOMETRI

Pencemaran plastik merupakan satu isu kritikal di seantero dunia di mana ia memerlukan kesedaran yang mencukupi untuk menyelesaikan proses pengurusan dan pelupusan sisa plastik. Kitar semula adalah satu langkah alternatif dalam mengatasi masalah tersebut. Mesin pencincang plastik adalah sebuah mesin untuk mencincang sisa plastik sebelum dikitar semula menjadi komoditi berfungsi. Reka bentuk mesin pencincang untuk perindustrian, perniagaan kecil hingga sederhana atau individu sedia ada. Kendatipun, prestasi pencincang dikekang oleh konfigurasi bilah, di mana pengagihan plastik yang tidak konsisten diperhatikan pada bilah. Maka, bahagian tertentu di bilah mengalami lebih banyak beban berbanding yang lain. Bilah mesin pencincang merupakan komponen utama mesin pencincang yang digunakan dalam kitar semula plastik. Pengesahan reka bentuk bilah mesin pencincang adalah penting untuk mewajarkan kesesuaian dan keselamatan untuk pemasangan dalam mesin pencincang. Variasi sudut pinggir (20°, 35°, dan 50°) bagi bilah telah dianalisis. Bilah plastic dengan sudut ponggir 35° dipilih kerana ia memberikan prestasi yang lebih tinggi dengan kelengkungan pegangan yang lebih besar. Penentuan tegasan von Mises maksimum, anjakan, dan tegasan ricih maksimum serta faktor keselamatan minimum bilah mesin pencincang bermata dua dan tiga kepada cincang helaian Polietilena Teraftalat (PET) telah dianalisis menggunakan Analisis Unsur Terhingga oleh perisian 'Fusion 360'. Keputusan berdasarkan daya tindak balas 1000N menunjukkan tegasan von Mises maksimum antara 159.70 MPa hingga 184.80 MPa, anjakan maksimum pada 0.03752 mm – 0.04611 mm, tegasan ricih maksimum julat dari 50.85 MPa – 71.86 MPa, dan faktor keselamatan 1.95– 2.25 bagi bilah pencincang bermata dua dan tiga. Reka bentuk kedua-dua bilah boleh diterima dan selamat kerana faktor keselamatan adalah lebih tinggi daripada piawaian faktor keselamatan terendah iaitu 1.5 berdasarkan piawaian kod tegasan dibenarkan. Kajian prestasi telah diimplementasikan pada bilah mesin pencincang pada geometri bilah mesin pencincang bermata dua dan tiga dalam orientasi pilin 'V' dan siri untuk memahami mekanisme haus dan cincangnya. Bilah berorientasi siri dikecualikan kerana kilasan tinggi dicipta menyebabkan ubah bentuk pada bahagian mesin pencincang. Pengenalpastian pengagihan beban di sepanjang bilah mesin pencincang diperhatikan dalam orientasi pilin dan 'V'. Struktur mikro dan kekerasan mata pemotong yang haus dan bilah mesin pencincang yang diterima telah dicirikan oleh mikroskop optik, mikroskop elektron imbasan bersama-sama dengan sinar-X tenaga sebaran (EDX), analisis belauan sinar-X (XRD) dan ujian kekerasan. Mekanisme haus dalam bilah mesin pencincang dikategorikan sebagai haus progresif. Haus progresif adalah disebabkan oleh haus lelas, perekat dan pengoksidaan. Haus lelas sebagai mekanisme haus progresif utama telah disahkan berdasarkan mekanisme cincang dan analisis struktur mikro pada bilah. Peningkatan unsur oksigen dalam EDX dan kehadiran magnetit dan hematit dalam analisis XRD membuktikan kehausan pengoksidaan berlaku pada retakan dan lekukan pada permukaan bilah. Kecekapan kitar semula, kecekapan mencincang dan peratusan penahanan adalah parameter yang digunakan untuk menilai prestasi bilah mesin pencincang. Kecekapan mencincang dalam semua geometri dan orientasi berjulat antara 64.83 ± 0.69% hingga 69.53 ± 1.32% dan cekap dalam mengitar semula plastik PET dengan kecekapan kitar semula melebihi 95%. Kombinasi terbaik bagi geometri dan orientasi ialah bilah mesin pencincang bermata dua dengan orientasi pilin yang mempamerkan kecekapan kitar semula pada 97.39±0.04%, kecekapan mencincang pada 69.53 ± 1.32%, dan peratusan penahanan pada 2.61 ± 0.04%, dengan bilangan bilah yang kurang mencatatkan haus teruk.

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LIST OF SYMBOLS

A	-	Cutting area made by edge of blade
t_h	-	Thickness of cutting edge
τ_{PET}	-	Shear strength of PET
r	-	Radial distance from centre of blades to the cutting edge
N	-	Rotational speed
w	-	Width of cutting edge
F	-	Reaction force acting on the edge of blade
F_s	-	Shredding force
T	-	Torque
P	-	Power rating of Prime mover
$[F]$	-	Reaction force matrix
$[K]$	-	Stiffness matrix
$\{\delta\}$	-	Displacement matrix
$[B]^T$	-	Transpose of strain-displacement matrix
$[D]$	-	Stress-strain matrix
$[B]$	-	Strain-displacement matrix
A_T	-	Area of triangular plane in free body diagram
$[\sigma]$	-	Maximum von Mises stress matrix
SME	-	Specific Mechanical Energy
t	-	Time taken
Q	-	Output mass of PET plastic
TP	-	Throughput
RE	-	Recycling efficiency
I	-	Input mass of PET plastic
R	-	Retained mass
SE	-	Shredding efficiency
Ms1	-	Pellets with size smaller and equal to 1cm × 1cm
Ms2	-	Pellets with size larger than 1cm × 1cm
ω	-	Angular speed
α	-	Offset angle
t_{gap}	-	Gap
ϵ	-	Relative error

LIST OF ABBREVIATIONS

FEA	-	Finite Element Analysis
PET	-	Polyethylene Terephthalate
HDPE	-	High Density Polyethylene
LDPE	-	Low Density Polyethylene
PVC	-	Polyvinyl Chloride
PP	-	Polypropylene
PS	-	Polystyrene
SEM	-	Scanning Electron Microscope
EDX	-	Energy Dispersive X-ray
XRD	-	X-ray Diffraction
DS	-	Double edges shredder blade in spiral orientation
DV	-	Double edges shredder blade in V-orientation
DC	-	Double edges shredder blade in series orientation
TS	-	Triple edges shredder blade in spiral orientation
TV	-	Triple edges shredder blade in V-orientation
TC	-	Triple edges shredder blade in series orientation
P	-	As-received shredder blade
C	-	Carbon
Si	-	Silicon
Mn	-	Manganese
S	-	Sulphur
P	-	Phosphorus
Fe	-	Ferum (iron)

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Plastic's versatility has led to its widespread use in a variety of industries, including food and beverage packaging, textile, automotive, manufacturing, and medical devices such as surgical equipment, drips, and pill blister packs (Chen *et al.*, 2021). The excessive and single-use usage of plastics, for instance personal protective equipment such as goggles and gloves due to the COVID-19 pandemic would certainly aggravate these projections (Silva *et al.*, 2020). The increasing usage of plastics has caused some substantial environmental pollution burden on both land and water habitats. Additionally, the non-biodegradable characteristic of plastic and inadequate plastic waste disposal management further trigger a slew of environmental issues (Bharadwaj *et al.*, 2015). To avoid a massive build-up of plastic in the environment, coordinated global action is urgently needed to reduce plastic consumption; increase rates of reuse, waste collection, and recycling; expand safe disposal systems; and accelerate innovation in the plastic value chain. Insufficient plastic waste treatment infrastructure for recycling purposes further restricted the operation of plastic recycling (D'Ambrières, 2019). Alternatively, recycling initiatives are critical. Therefore, plastic shredder machine was proposed at the recycling centre as the primary machine for the recycling process.

Shredder machine was utilised to shred the waste plastic into tiny sizes before converting it into a functional commodity. In general, there are two types of shredder which are defined by the number of shaft of shredder blades (Ekman R, 2018; Rathnam A V & Babu, 2017). A single shaft shredder equipped with only one shaft rotary blades, while a double shaft shredder is built with two shafts of blades. The shredder machine mainly consisted of four fundamental components: (i) a shaft and a set of shredder blades, (ii) a motor, gears, bearing, and transmission, (iii) a hopper, and (iv) a framework.

The most complicated consideration is the geometries and orientations of the shredder blades which directly influence the efficiency of the shredder machine (Hakkens, 2020). There are various geometries design of shredder blades with different number of cutting edges for instance double (Ravi Sekar, 2018), triple (Nasr & Yehia, 2019), quadruple (Ekman R, 2018), and sextuple (Rathnam A V & Babu, 2017) edges blades. Rathnam A V & Babu (2017) compared double and sextuple edges shredder blade and discovered that the greater number of edges reduced the shredding performance and increased the risk of workpieces to skip and wind up on the shredder blade. Similar occurrences were observed by Ekman R (2018) and Ravi Sekar (2018), where the greater number of cutting edges deteriorated the shredding performance. Meanwhile, VijayAnanth S *et al.* (2018) developed a triple edges blade in a double shafts shredding machine and reported a great shredding performance.

The shredding action occurs when the single shaft rotates, and the plastic workpieces are shredded by the rotating and fixed shredder blades. Example of plastic workpieces are polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP) and polystyrene (PS). During the shredding operation, the shredder blade generally directs the workpieces to be shredded between two sets of blades arranged along with two parallel axles. Shredding occurs at the intersection of the two opposing sets of blades that are interlaced with overlapping radii of the opposite axes. Several orientations such as spiral (Ravi Sekar, 2018), zigzag (Siddiqui F *et al.*, 2017), series (Kumaran P *et al.*, 2020), and V-orientation (Ekman R, 2018) were utilised on the shredder blades for the shredding process. Various blade geometries and orientations in the shaft might constrain the efficiency of the shredding, which creates inconsistent workpiece load distribution, resulting in certain sections of the blades experiencing higher load compared to the others.

Shredder machine designs for industrial, small to medium businesses or individuals are readily available, but the shredding output is constrained by the orientation of the blades. The inconsistent plastic distribution due to the blades' orientation caused certain sections of the shredder blades to experience more load compared to others. Plastic workpieces often appear to get trapped between blades. Further development is necessary in the plastic shredding by deciding the optimal blade geometry to be used. This research investigates the influence of different geometries and orientations of the shredder blade on the wear mechanism and the blades performance. Evaluation on the performance of the shredder machine was according to the recycling efficiency, shredding efficiency, and percentage retention.

1.2 Problem Statement

Shredder blade is the main component in a shredder machine. The performance of the shredder blades is affected by the geometry and the orientation of the shredder blades. In this study, the geometry refers to the number of cutting edges in a shredder blade. The strength of the cutting edge of shredder blades are vital to be determined to maintain the performance and safety of the blades' design during the shredding process (Nasr & Yehia, 2019; Zhou *et al.*, 2016). The design of different edge angle at the sharp cutting edge might affects the strength of the shredder blades. This could lead to high possibility of deformation occurred at the sharp cutting edge and required frequent replacement of blades (Nasr & Yehia, 2019; Rathnam A V & Babu, 2017). Thus, the study of strength analysis using finite element analysis on the blades' design with different edge angle is important to ensure the shredding performance and reduce the maintenance and replacement cost.

During the shredding process, the workpiece loading distribution varies based on the blade geometries and orientations in the shaft, which might constrain the efficiency of the shredding resulting in certain sections of the blades experience higher load compared to the others (Hakkens, 2020). The residue of the plastic material might trap at the cutting edge of the shredder blades that further interrupt the shredding process. This will require reversal of shaft therefore disturbs the shredding process flow. Hence, the distribution of workpieces in different shredder blades' geometries and orientations is crucial to be identified to determine the certain section of blades experienced higher impact that required regular maintenance to sustain the performance of the shredder machine.

The shredding process primarily involved a dry impact/sliding, which induced a shear deformation on the workpieces, such as PET. It may cause severe wear on the shredder blades, especially at the sharp cutting edges (Ezugwu *et al.*, 2003; Neugebauer *et al.*, 2011; Tao *et al.*, 2021). Consequently, the shredder blades required regular maintenance due to wear and tear during the shredding process. Thus, a precise design of the shredder blade geometry was vital in controlling and improving the wear resistance during the shredding processes (Ezugwu *et al.*, 2003). This has driven the demand for further studies into the wear behaviour of the shredder blade in various geometries and orientations during the shredding process (e.g., sliding wear and impact wear) (Abbasi Erfan *et al.*, 2018; Tomita, 2000). Although several investigations on the shredding performance have been performed, fewer studies were done for the analysis on the wear behaviour of the shredder blades (Ayo AW. *et al.*, 2017; Hakkens, 2020; Oyebade D *et al.*, 2019).

This research highlights the study of the of the blades design in different geometries with various edge angle, and investigation on the influence of different geometries and orientations of the shredder blade on the wear mechanism with blades performance. Evaluation on the performance of the shredder machine was according to the recycling efficiency, shredding efficiency, and percentage retention.

1.3 Research Goal

The aim of this project is to investigate the shredding pattern in different blades' orientations and geometries, and its shredding performance. The main objectives of the study are:

1. To investigate the strength of the shredder blade's design in different geometries with various edge angle using finite element analysis.

2. To investigate and analyse the wear mechanisms of shredder blades with various geometries and orientations.

3. To evaluate the performance of shredder blades with various geometries and orientations.

1.4 Research Methodology

a. Design and strength study of plastic shredder machine and blades.

The plastic shredder machine consists of several parts which are the frame/stand, hopper, transmission system and gears, the shaft, and blades. The geometry and orientation of the shredder blades varies whilst other parts of the shredder machine were fabricated according to the blueprint in the Precious Plastic website which is accessible for free (Precious Plastic Universe, 2020). There are three blades' orientation identified for investigation which are the spiral, V-orientation, and series. The geometry of the blade varies based on the number of cutting edge (double and triple edges). The shredder blades are the most essential part in the shredder machine. Thus, simulation study using finite element analysis (FEA) was carried out to justify the design of the blade for their suitability and safety to be installed in the shredder machine. The shredder machine components are made up of low carbon steel or mild steel.

b. Plastic waste collection and preparation.

To obtain reliable data for comparison of shredder blades wear under various blades' geometries and orientations, the type, size, shape, and thickness of the workpieces to be shredded remained constant. Used PET bottles were selected as the workpieces to be shred due to its availability. (Disclaimer: To avoid degradation of plastic quality, PET bottles that immediately disposed of by the user were collected and the bottles are avoided to be exposed to the heat (sun) for more than a week).

c. Shredding process and experiment outputs.

The shredding process is carried out separately in three different orientations (spiral, V, and series orientations) with two types of blades' geometries (double edges and triple edges). The edge angle of the shredder blades was determined using finite element analysis before the fabrication process. The distribution of PET (workpieces) during shredding was identified, and the wear of the blade in each geometry and orientation was analysed on selected blades. The size of shredded PET plastic was determined. The shredding performance of shredder blades in each geometry and orientation was analysed.

d. Data Analysis.

Identification of the loading distribution along the shredder blades was observed in different orientations. The microstructure of worn cutting edge of the shredder blades were examined under optical microscopic and scanning electron microscopic (SEM) along with elemental composition by energy dispersive X-ray microanalysis (EDX) before and after shredding of PET. A Rockwell hardness machine is used to identify the hardness of the shredder blade before and after the shredding process. Crystalline structure on the shredder blade was analysed by X-ray diffraction (XRD).